The overall objective of the research was to set up facilities to generate transient magnetic fields in the megagauss range. The principal application envisaged was the eventual combination of megagauss targets with high energy accelerator beams to test fundamental features of quantum electrodynamics. Both of these objectives were met within the duration of the grant. This report summarizes the principal results of the research.
0. ABSTRACT

Support was provided by the U.S. Army Research Office, Durham, with the overall objective of enabling our laboratory to set up facilities to generate transient magnetic fields in the megagauss range. The principal application envisaged was the eventual combination of megagauss targets with high energy accelerator beams to test fundamental features of quantum electrodynamics. Both of these objectives were met within the duration of the grant. Our Laboratory has built the following megagauss generators:

<table>
<thead>
<tr>
<th>Device</th>
<th>Peak Fields Attained</th>
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</thead>
<tbody>
<tr>
<td>Pulsed coil devices</td>
<td>2.2 MG</td>
</tr>
<tr>
<td>Electromagnetic implosion (Chare effect) devices</td>
<td>1.6 MG</td>
</tr>
<tr>
<td>High explosive generators</td>
<td>4.2 MG</td>
</tr>
</tbody>
</table>

An experimental series designed to test radiation reaction and quantum effects in magnetic Bremsstrahlung was carried out with complete success at the Stanford Linear Accelerator Center during the period June - November 1970.

1. SUMMARY OF PRINCIPAL RESEARCH RESULTS

(All references are collected in the Bibliography, Section 3: The reference code [6a] for example, means paper #6 listed in Section 3a).

(a) Flux Compression (Experimental):

(i) Explosive Flux Compression. - A total of approximately 28 complete megagauss experiments in which the fields were generated by means of explosively driven devices, were conducted during the period 1967 - 70. Two
principal types of generators were developed: 1) Cylindrical ("doughnut")
devices employing 24 SE-1 detonators and composition B and PBX explosive
lenses weighing approximately 11 lbs. These devices were fired in conjunction
with a 30 kJ seed field bank, and peak fields of the order of 1 MG were
measured. An exceptional feature of the IIT experiments is that excellent
cylindricity of the implosions were achieved and documented with framing
camera records. This work is described in [1c], [2c], [6c], [31a], [5b],
[6b]. 2) Cylindrical (Top Hat) compression devices employing only one SE-1
detonator and about one pound of "Detasheet" explosive. Peak fields of 4.2
MG were recorded with these devices. See [12a], [31a], [17b] and [6c].

(ii) Electromagnetic Flux Compression (Cnare Effect). - Extensive
parameter studies were carried out in order to determine empirical optimizing
ranges for the EMC technique. The performance of these devices turned out
to be unexpectedly sensitive to variations in the ratio of the height of
the primary coil to the height of the Cnare foil, as well as the mechanical
temper of the Cnare foil. Peak fields of the order of 1.6 MG were generated
with a 60 kJ capacitor bank. See [17a], [31a], [9b], [16b], [5c].

(b) Flux Compression (Theoretical):

Extensive studies were undertaken to clarify the operation of mega-
gauss devices, to discover optimizing techniques and to extract solid state
physics information on matter under extreme conditions. In particular, we
examined the magnetic field injection mechanism in flux compression devices
[2a], [12a], [22a], [7b], [2c]; start-up, take-over, and intermediate field
flux compression [12a], [14a], [15a], [19a], [20a], [22a], [25a], [30a],
[31a], [2b], [11b], [15b], [17b], [5c], [6c]; the conditions associated with
the terminal or "turn-around" stage of flux compression were studied in [14a],
[17a], [20a], [25a], [12b], [5c] and [6c]. Techniques for data reversion
were developed which permit one to infer the resistivities and energy transfer
efficiencies of the liners during the implosion phase [14a], [20a], [30a],
[31a]. Analysis of the results from a wide variety of implosion devices
indicates that the resistivities of the liner materials under megagauss con-
ditions remain at relatively low values.

(c) Applications to Quantum Electrodynamics:

(i) Theoretical Studies. - The range of possibilities for quantum
electrodynamics experiments accessible with the combination of megagauss
targets and high energy accelerator beams was studied in [1a]. This survey
indicated that the most promising line of investigation involved magnetic
Bremsstrahlung [9a], [1b], [18b].

(ii) Megagauss Bremsstrahlung Experiment at Stanford Linear Accelerator
Center. - A specific proposal to measure magnetic Bremsstrahlung in the
20 GeV beam of the Stanford Linear Accelerator Center was presented in [9a]
and an experiment was designed. Megagauss targets utilizing pulsed coils
and Cnare implosion were both successfully tried during the course of the
SLAC program. A total of 15 complete megagauss-accelerator experiments were
carried out. Sometimes as many as 4 MG shots, including both coil and im-
losion configurations, were completed in a single day. Preliminary results
of the experimental series at SLAC were reported in [23a], [24a], [20b], [22b].
The final results are collected in [32a], [7c], [8c]. Analysis of the results indicates that the Bremsstrahlung spectrum agrees with theoretical predictions. The absolute radiation rate expected is also within the limits of experimental error. However, the observed electron deflections are consistently higher by about 10% than the calculated values. This last point is still undergoing critical analysis and subsidiary experimental checks.

(d) Megagauss Fields Produced with Coils:

A capacitor bank termination adaptable to coils was originally built for the Stanford experiment in order to provide a back-up of reliable medium intensity fields of circa 0.7 MG. However, the coils that were designed proved to be better by factors of 2 and 3, so that peak fields of 2.2 MG could be reliably and repeatedly generated. These coils exploded concentrically with negligible damage to devices placed in the interior field region; so, for example, emulsion pellicles and delicate field probes survived MG coil shots. These coil generators are now being adapted for solid state physics experiments. (Magneto-reflectance of laser beams [Prof. J. Davis, private communication]). [13a], [22a], [24a], [32a], [19b], [21b], [7c], [9c].

(e) Hysteresis and Fatigue:

An auxiliary program of research concerned with hysteresis and fatigue in magnetic cooperative systems, structures, and materials has also been carried out. A new general criterion for the shake-down of structures has been developed and checked against known results in structural engineering. Furthermore, a general theory of hysteresis has been developed. Applications to metal fatigue are now being studied. [4a], [5a], [6a], [18a], [21a], [26a], [27a], [28a], [29a], [3b], [8b], [10b], [14b], [1c], [3c].

2. CONSTRUCTION OF LABORATORY FACILITIES

It was pointed out in the original proposal to AROD that a research program of this magnitude could not be organized around a few specific experiments, but rather that an entire range of facilities adequate for carrying out studies of flux compression was absolute essential. Accordingly, special laboratory facilities were constructed at the IIT campus for carrying out all "indoor" experiments --- specifically megagauss shots involving coils for electromagnetic implosion generators. The "outdoor" experiments which necessitated the detonation of high explosive devices were conducted at a special bunker complex built at the IITRI firing range at La Porte, Indiana. These facilities are among the most sophisticated of their kind available at any university laboratory in the United States. [3a], [31a], [4b], [5b], [6b], [1c], [2c], [5c], [6c].
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     R. Gearhart, H. H. Heckman)

(b) Papers Presented at Conferences:

   High Energy Magnetic Bremsstrahlung (T. Erber)

   Principles of Magnetic Flux Compression
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   Nonequilibrium Statistical Mechanics of a Four-Magnet System
   (T. Erber and H. G. Latal)

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   (T. Erber, G. K. Forsberg, H. G. Latal, J. A. Mazzie, J. E. Kennedy)

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   Study of a Magnetic Compression System
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2. M. S. Thesis (1967)
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   Electromagnetic Flux Compression (D. Kachilla)

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   (J. E. Kennedy)

   The Production of Megagauss Magnetic Fields for the Stanford Magnetic
   Bremsstrahlung Experiment (R. C. McBroom)

   Emulsion Analysis of Megagauss Bremsstrahlung Experiment (M. Mashkour)

   Analytical and Numerical Treatment of Nonlinear Magnetic Diffusion
   (M. E. Roux)

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4. **LIST OF DEGREES AWARDED:**

- G. K. Forsberg  M. S.  1966
- J. A. Mazzie    M. S.  1967
- G. R. Marousek  M. S.  1967
- C. H. Shih      Ph. D. 1968
- D. Kachilla     M. S.  1969
- J. E. Kennedy   Ph. D. 1970
- R. C. McBroom   M. S.  1971
- M. Mashkour     Ph. D. 1972
- M. E. Roux      M. S.  1972
5. SCIENTIFIC PERSONNEL

T. Erber, Professor of Physics, IIT (1964 - )
F. Herlach, Professor of Physics, IIT (1967 - )
H. G. Latal, Visiting Associate Professor of Physics (1965 - 67, 1968 - 70)
M. Guillot, Post-Doctoral Research Associate (1967 - 68)
L. Kirchner, Technician, Part-Time (1965 - 68)
E. Petit, Technician (1969 - )
M. Roux, Secretary, Half Time (1969 - 72)